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Climatic and human-related indicators and their implications for evapotranspiration management in a watershed of Loess Plateau, China

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ABSTRACT

Climate change and human activities are the two most important factors affecting water resource in Yellow River Basin, and Yellow River Basin is the most serious and prominent water shortage area in China. It is of great significance to study the impact of climate change and human activities on hydrology process in mountain areas of for water resources management. In this research, one typical watershed in the third sub region of the Loess Plateau was studied through the adoption of Zhang model. Water balance equations were established through analyzing the actual evapotranspiration from 1986 to 2016. Also, responses of evapotranspiration to climate change and LUCC were quantitatively distinguished as while. The results showed that the actual evapotranspiration was acquired by the method of water balance. During the Mann-Kendall test, the data could not produce sudden break. The actual evapotranspiration decreased along with the increase of the potential evapotranspiration. Comparatively, it increased to certain degree as the rainfall, relative humidity, temperature and wind speed increased while decreased with longer sunshine hours. Human activities played a dominant role in evapotranspiration variations, contributing approximately 90% to its change. Only 10% was contributed by precipitation factor. Large-scaled activities of the conversion from the sloping farmland to terrace were implemented in the middle 1980s in the studying Luoyugou watershed, remarkably influencing the regime of runoff generation and accordant junction. This is consequently leading to spatial-temporal variability in evapotranspiration.

1. Introduction

Climate change has been a serious challenge to the existence and development of human beings and a major global issue of concerns to the international research and governmental community. Actively responding to climate change has become an international consensus (Creed, 2015). Water resources are the most direct and important sector that are significantly affected by climate change. Moreover, many anthropogenic activities are also affecting dynamics of water resources particularly in many watersheds that are greatly subject to highly changing environmental conditions of human being and climate change. Over the past decades, analysis of hydrological cycle under changing environment has become one of the hotspots in water science research. As the utmost important area in China, the Loess Plateau is vulnerable both to any changes of human activities and climatic conditions, leading to significant changes to local rivers (Feng et al., 2016; Fu et al., 2016; Liu et al., 2018). More recently, phenomenon of water resources reduction in China has attracted wide attention from government decision-making departments and the public. Therefore, it is significant to study the effects of climate change and LUCC (Land Use and Land Cover Change) on actual evapotranspiration.

Different land use types have different vegetation covers, leaf area indexes, root depths and albedos, which correspondingly have different evaporation rates (Cheng, 2009; Ivan, 2009; Xu and Yang, 2010; Tabari, 2010; Forbes, 2011; Liu et al., 2018; Liu et al., 2015). Forest-water relationship is a hot and important issue in ecohydrology studies. With the worsening of the environment and the awareness of the ecological benefits of forests, many countries or regions are actively conducting reforestation effort to increase forest coverage. However, reforestation could also potentially reduce water capacity (Scott et al., 1998; Jackson et al., 2005; Sun et al., 2006; Lv et al., 2018). To address the growing soil erosion and desertification, China had implemented many large-scale reforestation programmes in the last decades, and the total investment reached ¥720 billion (114 billion dollars) (Yao et al., 2011).

The close relationship between evapotranspiration and leaf area index have attracted lots of attention (Roland, 2000; Glenn, 2010; Liu

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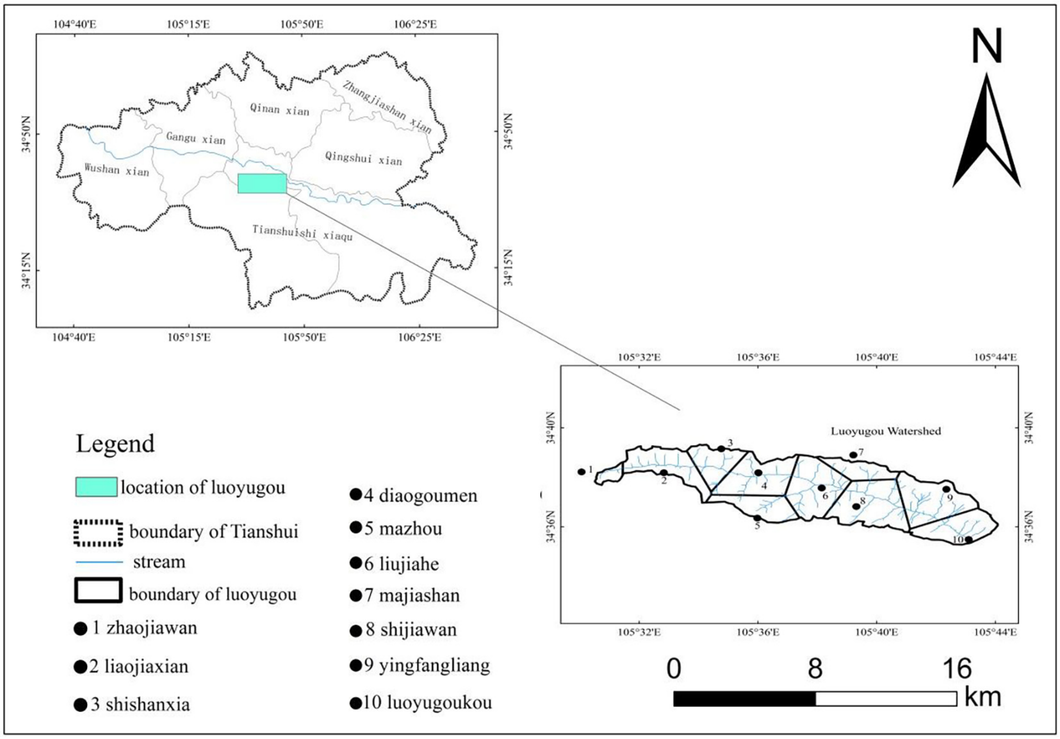

Fig. 1. The location of Luoyugou watershed in this research.

et al., 2017). The impact of different vegetation cover of different watersheds showed that the decrease of forest cover could generally lead to the increase of runoff and the decrease of evapotranspiration (Chiew, 1994; Allen, 1998; Eckhardt, 2001; Temesgen, 2004). Forest vegetation on evapotranspiration vertically has obvious effect of spatial variation (Hibbert, 1983; Flaschka, 1987; Hornbeck, 1993; Dunn, 1995; Deng, 1998; Kell, 2001). The proportion of transpiration of total evapotranspiration ranged from 43% to 68% from dry season to wet season and surface evaporation took a tiny proportion of the absolute difference of total evapotranspiration and plant transpiration (Kell, 2001; Thomas, 2003). Some research showed that canopy transpiration occupied a big percentage of total evapotranspiration (Gao, 2002; Xiong, 2005; Cheng, 2003). Gao (2002) studied 5 types of main forest in Liaoning, indicating that the total evapotranspiration in growth season ranged from 476.6 mm to 651.3 mm, occupying 11.4–26.5% of the total season. Besides, forest vegetation on evapotranspiration horizontally has obvious effect of spatial variation. Xiong (2005) held an opinion that the total forest evapotranspiration was bigger than non-forest land. Cheng (2003) in Gongga Mountain founded that in non-growth season the forest evapotranspiration was approximately 25% lower than non-forest land and in growth season the forest evapotranspiration was approximately 25% higher than non-forest land. In total, forest can increase evapotranspiration.

Many factors could affect water yield, such as climate, topography, soil and vegetation. The classic paired catchment studies have been widely used as a means of determining changes in water yield resulting from forest change excluding the effects of other environmental variables (Brown et al., 2005). For example, Zhang et al.(2007) used the water balance model to analysis the impact of forest on mean annual runoff (MAR), based on the existing data sets of MAR and forest coverage. Learning from their researches, we also use this approach in our study.

In recent years, theories and methods represented by hydrothermal coupling equilibrium have gradually become the frontier and hotspot in the field of international hydrology. Budyko hypothesis theory is a typical representative of water-heat coupling equilibrium and one of the most widely used theoretical foundations in watershed hydrological process research. In the study of underlying surface impacts, the main research methods are still traditional statistical analysis methods, or simply considered as the difference between runoff change and climate change impacts (Xu et al., 2014). These results are only numerical calculations, but lack of theoretical analysis.

Based on the Budyko hypothesis, the objectives of this study were to (1) analyze the changes of the actual evapotranspiration from 1986 to 2016 in the Luoyugou watershed, which is a typical watershed in the third sub region of the Loess Plateau; (2) analyze the effects of climate change and human activities on the actual evapotranspiration.

2. Material and methods

2.1. Overview of the studying area

Luoyugou watershed is long and narrow with a total area of 72.79 km^2. The watershed can be divided into rocky mountainous, variegated soil, and loess areas. Annual average precipitation is 548.9 mm, with a minimum of 330.1 mm and maximum at 842.2 mm. Precipitation in June to September comprises more than 60% of the year's precipitation, the rain, and the heat. The elevation varies from 1175 to 1707 m above sea level, and had relative height difference of 532 m. Annual average temperature is 10.7 °C, and the frost-free period lasts for 184 days. Eleven soil types can be found in this watershed, with mountain grey cinnamon soil as the typical zonal soil, covering 91.7% of the whole watershed. Farmland covers 55%, whereas natural vegetation comprises approximately 30.0% of the watershed. All arbor trees in the watershed were planted, whereas the bushes and shrubs are indigenous. The intensity of gully erosion is far more than slope erosion. Gravitational erosion development is apparent (Fig. 1).

2.2. Data

The data of rainfall, runoff (1986–2016) were obtained from Tianshui Soil and Water Conservation station, Yellow River

Conservancy Commission of the Ministry of Water Resources. Which, the daily rain data are got from 10 rain-gauge stations in the watershed, and the annual runoff data are got from the measured data by the Tianshui Soil and Water Conservation station. To explore the water resources in watersheds of loess, observation web was set up in Luoyugou watershed (Fig. 1).

On the basis of data in every rain-gauge station, daily precipitations and maximum precipitation in every period were built up in these watersheds. Daily average flow data were recorded in all watersheds. Runoff-time curves were drawn after each precipitation with total runoff amount. One or two water samples were obtained to calculate daily average sediment concentration and sediment transport rate.

2.3. Zhang model

According to Budyko (1974), the ratio of evapotranspiration (ET_a) to precipitation (P) is a function of the ratio of potential evapotranspiration (ET_P) to precipitation (P), and that is:

$$ET_a/P = f\,(ET_P/P) \tag{1}$$

In dry climate, ET_P is higher than rainfall and ET_a is close to rainfall, while in wet climate, available water is higher than ET_P, which is close to ET_a. Based on this understanding, Budyko proposed under drought conditions: runoff/rainfall tended to 0, the actual evapotranspiration/rainfall was close to 1, the runoff/rainfall tended to infinity; in wet conditions, the actual evapotranspiration was close to runoff.

Based on that and the data of 250 catchments around the world, Zhang et al. (2001) introduced a dimensionless parameter and simulates the relationship between the above functions, and then, a statistical model of two parameters is proposed, the model can simulate the annual average evapotranspiration of the basin scale. So, Zhang et al proposed potential evapotranspiration PET's formula by converting AET:

$$ET_{\mathrm{a}} = \left[\frac{1 + \omega\frac{ET_p}{P}}{1 + \omega\frac{ET_p}{P} + \frac{P}{ET_p}}\right] \times P \tag{2}$$

where P, ET_a, ET_P are annual average rainfall, actual evapotranspiration, potential evaporation, respectively, with a common unit of mm. ω is a dimensionless parameter of the underlying surface in the watershed.

3. Results

3.1. Annual and tendency changes of actual evapotranspiration

By water balance method, annual actual evapotranspiration was obtained (Fig. 2). Base on Fig. 2, the actual evapotranspiration went upward during 1986–2016 generally and the trend between 1994 and 2000 was low, which was because that the rainfall in this period of time was rare. After 2003, it showed an increasing trend and the correlation coefficient was 0.091.

With the calculated actual evapotranspiration based on the water balance method and the different evapotranspiration inter-annual variation in the process of mutation based on M-K test (Fig. 3(a)), t test analysis (Fig. 3(b)), due to runoff, erosion and evapotranspiration data series was short, so the jump parameter Jy was taken as 2 when test. From Fig. 3, Z1 and Z2 curves weren't crossed during the M-K test, combined with the t test, it showed that the actual evapotranspiration in the studied sequence, Z1 and Z2 had no crossing point, indicating that the actual evapotranspiration had no significant change and the mutation wouldn't occur.

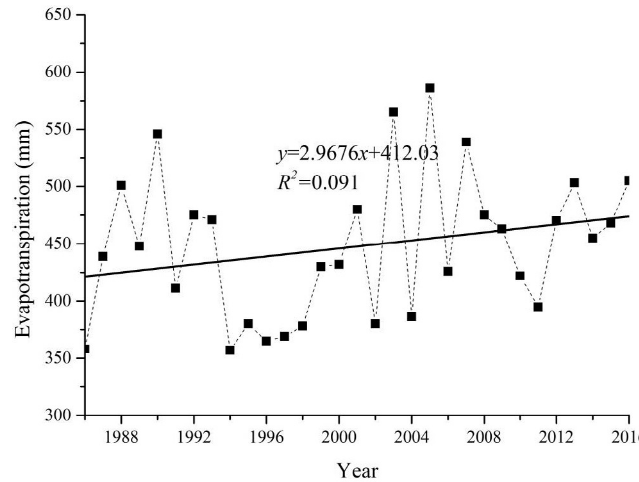

Fig. 2. Annual actual evapotranspiration change from 1986 to 2016.

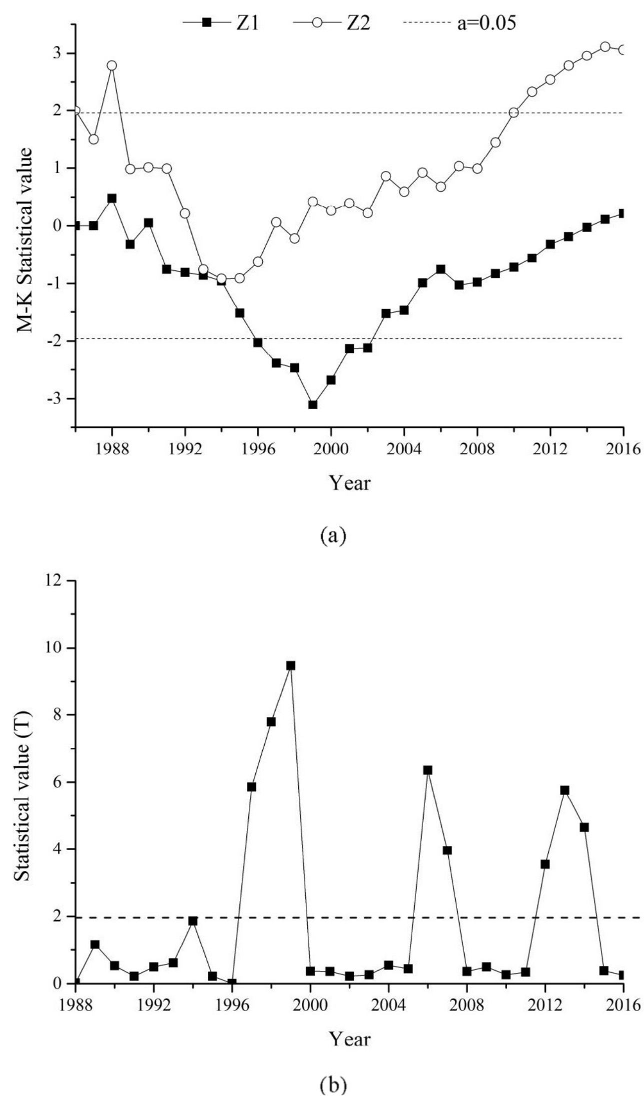

Fig. 3. Non-parametric test statistical value for actual evapotranspiration.

3.2. Prediction on actual evapotranspiration by Zhang model

Based on four land use data (1986, 1995, 2006, 2016) in the watershed, using evapotranspiration calculated by the water balance

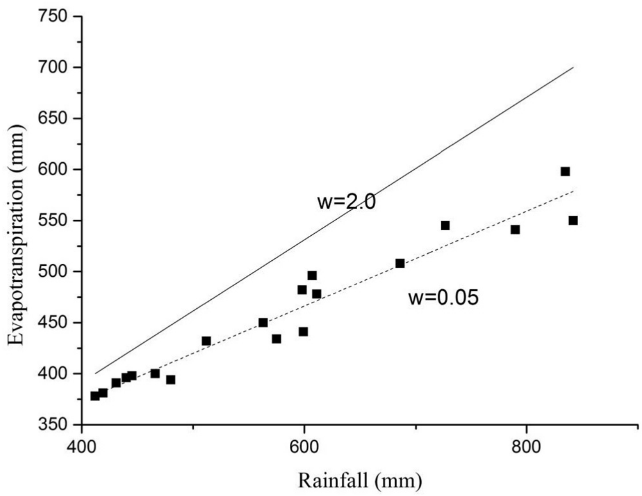

Fig. 4. Calculated evapotranspiration by Zhang model.

method as the measured value, evapotranspiration calculated by Zhang model as the prediction.

It can be seen from Figs. 4–6, evapotranspiration calculated by Zhang model was close to the W = 0.5 line, it was determined by the proportion of woodland area, which occupied only 10.83% of the whole area in 1986 and increased to 13.95% in 2016. The measured evapotranspiration obtained was larger than predicted evapotranspiration, mainly because there were two aspects, the first was that in the calculation of evapotranspiration process by water balance method, the soil water storage couldn't be 0 and this method was more applicable for many years used to calculate evapotranspiration; the second was that in the calculation process of evapotranspiration in the study area by Zhang model, w was small, which was similar with Wang Shengping's conclusion in the calculation of evapotranspiration in Lv'ergou watershed (Wang et al., 2006). In addition, in the calculating for evaporation process by these two methods, when the rainfall was small, the two curves would intersect at one point; in arid areas with small rainfalls, similar results would be obtained by these two methods.

3.3. Response of climate change and land use to actual evapotranspiration

It can be seen from Fig. 7, the correlation between the rainfall-evapotranspiration double cumulative curves were significant, and the correlation coefficient reached almost 1.0, differences between the pre-period and the post-period were small, mainly due to the large

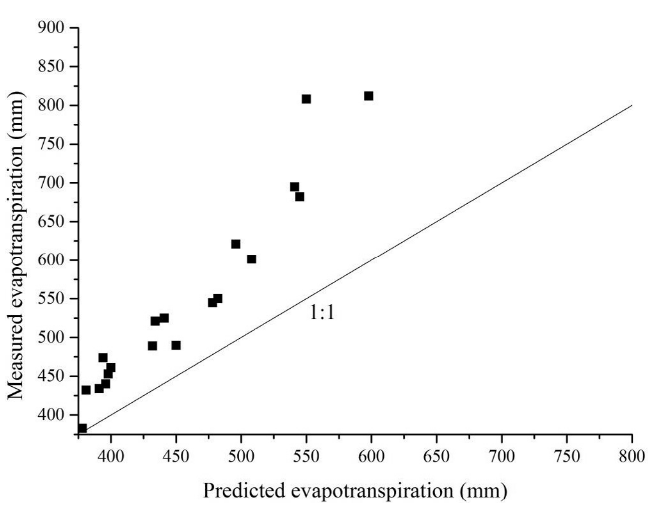

Fig. 5. Predicted and measured evapotranspiration comparison.

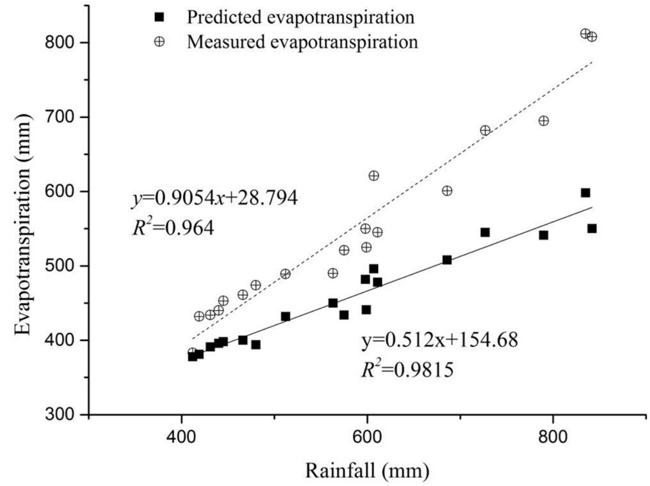

Fig. 6. Correlation between predicted and measured evapotranspiration.

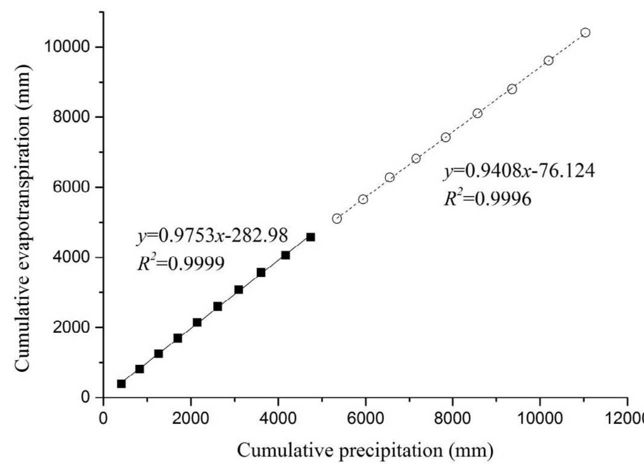

Fig. 7. Double mass curve of annual actual evapotranspiration and annual rainfall in the watershed.

Table 1
Impact of human activities and rainfall variation to evapotranspiration.

	Total change	Human activities	Rainfall variation
effect quantity (10^4t)	102.99	93.73	9.25
Contribution rate (%)	100	91.01	8.99

influence of rainfall on evapotranspiration.

From Table 1, human activities had a large impact on the actual evapotranspiration. In the sequence of study period, the impact of human activities occupied 90% of the total evapotranspiration, while the rainfall accounted for 10%. This was mainly due to the change of the underlying surface by human activity. By implementation of forest and grass, sloping land into terraced fields and constructing dams and other measures to reduce surface runoff, increasing vegetation cover, making the increase in evapotranspiration.

4. Discussions

The small scale (10 km^2) watershed experiments have limitations in answering large-scale questions. As the size of a watershed increases, the hydrological processes become more complex because of the inclusion of more landforms (wetlands, ponds, lakes, etc.) and land uses (agriculture, urban areas, mining, etc.). However, many important hydrological issues such as urban floods, navigation, and sedimentation

occur at large watershed scales. This highlights an important need to conduct large-scale forest hydrology. Therefore, the key purpose of this paper is how forest impacts the high flow and low flow at watershed-scale.

The paired catchment approach is the best means of determining the magnitude of water yield changes resulting from changes in vegetation (Brown et al., 2005). Because of the limited number of paired catchments, accurately calculate the impact amount of forest on water yield cannot be convincing. It is important to highlight that there remains a lot of uncertainty in this statistical analysis of forest impact on water yield. In addition to precipitation and forests, other meteorological factors (e.g. the temperature) and terrain factors (e.g. the slope) also could affect the water yield. This study area is located in the same climatic zone and mostly is the rocky mountain area, and its meteorological and topographical factors have little change, but after all causing a deviation of our research results. Due to the lack of paired catchments, it's difficult to remove these additional factors.

In the past century, research on forest-water relationship has made great progress worldwide. Even today, this topic remains a hot issue in ecohydrology studies. Because China is facing severe ecological and environmental problems, especially water shortage and severe soil erosion, the Chinese government has initiated several large-scale forestation programs (e.g. the three north shelterbelt) to solve these problems (Li, 2004). Soil erosion really been controlled (Wang, 1992), but we ignored the fact that forest evapotranspiration consumes vast amounts of water, and resulted in more serious water shortages, especially in the arid north China, that also caused serious soil desiccation (Li et al., 2008) and water yield reduction (Huang et al., 2003a,b; Zhang et al., 2007; Wang et al., 2008; Yu et al., 2009). This allows us to start the correct view of the ecological functions of forests. At the same time, it forced many researchers and governors to pay more attention to the relationship between forestation and water yields. Wei et al. (2008) noted that the time for the "widespread debate on forest and water in China is coming." Although research literature on this issue has grown substantially since the early 1990s, the results of the studies differ.

The key to predict and understand the forest impact is to know which water balance component is "the winner" in affecting water yield (Wang et al., 2011). Precipitation is the most important source of runoff, the increase in precipitation will inevitably bring about increased runoff. Forests can enhance the ET and then decrease water yield. Paradoxically, forests can also enhance the soil infiltration which leads to greater percolation to groundwater and thus later could contribute towards low flow discharges (Bruijnzeel, 2004).

Human activities affect the regional water cycle process by changing the underlying surface type. There are many factors affecting the runoff of the river basin, such as land use change, water conservancy projects, water resources development and so on. The Yellow River basin is one of the regions most seriously affected by human activities. Most studies have shown that the impact of human activities on river basin runoff is much greater than that of climate change. The results of this study also show that the contribution rate of precipitation change is only 8.99% and that of human activities is 91.01% in the process of runoff change in studied catchment. These may provide reference for water resources management in the Yellow River basin.

5. Conclusions

In this study, we use the Zhang model and water balance equations to analyze the actual evapotranspiration from 1986 to 2016 in the Luoyugou watershed, which is a typical watershed in the third sub region of the Loess Plateau. The conclusions can be summarized as follows:

1) The actual evapotranspiration went upward during 1986 to 2016 generally and the trend between 1994 and 2000 was downward. After 2003, the actual evapotranspiration had no significant change and the mutation wouldn't occur;
2) Evapotranspiration calculated by Zhang model was close to the W = 0.5 line, it was determined by the proportion of woodland area, which occupied only 10.83% of the whole area in 1986 and increased to 13.95% in 2016;
3) Human activities had a large impact on the actual evapotranspiration. In the sequence of study period, the impact of human activities occupied 90% of the total evapotranspiration, while the rainfall accounted for 10%.

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Appendix A

Mann-Kendall trend detection

Mann-Kendall test is one of the most widely used non-parametric tests to detect significant trends of climatic variables in time series (Hamed, 2008; Liang et al., 2010). It is based on the statistic S:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \tag{3}$$

$$sgn(x) = \begin{cases} 1, & if \quad x_j - x_i > 0 \\ 0, & if \quad x_j - x_i = 0 \\ -1, & if \quad x_j - x_i < 0 \end{cases} \tag{4}$$

where x_i and x_j are two generic sequential data values of the variable, n is the length of the data set.

The null hypothesis H_0 is that there is no trend in the dataset, and the statistic S is approximately normally distributed with a mean of zero. For data sets with more than 10 values, the variance associated with the statistic S (*Var(S)*) can be calculated as:

$$Var(S) = \frac{n(n-1)(2n+5)}{18} \tag{5}$$

The values of S and *Var(S)* are used to compute the test statistic Z as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}, & if \quad S > 0 \\ 0 & if \quad S = 0 \\ \frac{S+1}{\sqrt{Var(S)}}, & if \quad S < 0 \end{cases} \tag{6}$$

The presence of a statistically significant trend is evaluated using the Z value. A positive (negative) value of Z indicates an upward (downward) trend. The statistic Z has a normal distribution. H_0 can be rejected at the significance level of α if $|Z| \geq Z_{1-\alpha/2}$, where $Z_{1-\alpha/2}$ is obtained from the standard normal cumulative distribution tables (Liu et al., 2014).

To conduct change-point analysis, the non-parametric Mann-Kendall test was employed. The test statistic S_k is defined as:

$$S_k = \sum_{i=1}^{k} \sum_{j=1}^{i-1} \alpha_{ij} \quad (k = 2, 3, 4, \cdots, n) \tag{7}$$

$$\alpha_{ij} = \begin{cases} 1 & x_i > x_j \\ 0 & x_i \leq x_j \end{cases} \quad 1 \leq j \leq i \tag{8}$$

Then, the definition of the statistic index UF is calculated as:

$$UF = \frac{S_k - E(S_k)}{\sqrt{Var(S_k)}} \quad k = 1, 2, 3, \cdots, n \tag{9}$$

$$E(S_k) = \frac{k(k-1)}{4} \tag{10}$$

$$Var(S_k) = \frac{k(k-1)(2k+5)}{72} \tag{11}$$

UF follows the standard normal distribution, which is the forward statistic sequence, and the backward sequence UB is calculated using the same equation but with a reversed series of data.

In the two sided test, if the null hypothesis is rejected, an increasing ($UF > 0$) or a decreasing ($UF < 0$) trend is indicated. If there is a match point of the two curves and the trend of the series is statistically significant, the match point would be regarded as the change point (Du et al., 2011).

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